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Cardiovascular surgery

Current practice

Edited by

THOMAS H. BURFORD, M.D.

Professor of Clinical Thoracic and Cardiovascular Surgery, Washington University School of Medicine; Associate Thoracic Surgeon, Barnes Hospital and Saint Louis Children's Hospital, Saint Louis, Missouri

THOMAS B. FERGUSON, M.D.

Associate Professor of Clinical Thoracic and Cardiovascular Surgery, Washington University School of Medicine; Attending Thoracic Surgeon, Barnes Hospital and Saint Louis Children's Hospital, Saint Louis, Missouri

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To the memory of

Richard H. Amberg

publisher, civic leader, and humanitarian

His concern for the sick and his efforts in their behalf made possible the development of the open-heart program at Washington University Medical Center.

Chapter 9

Ventricular assistive devices

*Present and future**

Michael E. DeBakey
Edward B. Diethrich

The need for effective mechanical assistance of the failing heart, which has been apparent for some time,[8] has recently been reemphasized.[3,6,9,12,14] The death rate of more than 75%[18] among patients having acute myocardial infarction and hypotension is impetus enough for development of an effective mechanical device to assist the failing left ventricle. The early enthusiasm for cardiac homotransplantation as possible treatment for irreversible heart failure has been dampened somewhat by the high incidence of uncontrolled cardiac rejection. Temporary support of a transplanted human heart, similar to that provided by the artificial kidney during renal rejection, might well extend the indications and long-term success of cardiac transplantation.[4]

Numerous mechanical assistive devices based on a variety of hemodynamic principles have been tested, both experimentally and clinically. Although no available method appears to provide the flexibility required to handle every cardiac crisis effectively, the feasibility of temporarily assisting the failing left ventricle by a mechanical pump has been clearly established during the past few years.[5,7] For example, patients with elevated left atrial pressure and poor left ventricular function immediately after valvular resection and prosthetic replacement are routinely supported by partial cardiopulmonary bypass until normal ventricular function is resumed. The left ventricular bypass pump, an extension of partial cardiopulmonary support, has been used successfully in patients during the immediate period after prosthetic valvular replacement until cardiac function became normal. In other patients with irreversible cardiogenic shock after myocardial infarction, cardiac support for varying periods has been provided by application of a diaphragm-type pump directly to the heart. A larger number of similar patients have received cardiac support by intermittent expansion of an intra-aortic balloon located in the descending thoracic aorta. These are only a few examples of the attempts to provide temporary support of the failing heart.[1] The success that has been achieved has provided encouragement for further research, especially in view of the great need for such devices.

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The patient with inadequate cardiac function may benefit in two ways by mechanical cardiac assistance. The classic studies of Sarnoff and associates[20] showed that the work load of the heart is proportional to the cardiac output multiplied by the systolic blood pressure, and that the oxygen consumption is equal to the mean left ventricular pressure times the length of ventricular systole. The work load and oxygen consumption of the heart can be reduced, therefore, by use of a mechanical assistive device, which lowers both the pressure against which the ventricle must expel blood and the pressure within the ventricle itself. Under these circumstances the requirements of the failing heart are reduced, and an opportunity for recovery is provided. In addition, inadequate peripheral perfusion of cerebral, renal, and hepatic arterial systems is obviated, and the function of these organs is restored to normal.

Despite the urgent need and extensive research, a completely satisfactory method of prolonged cardiac assistance for all severe cardiac conditions remains to be developed. Various kinds of mechanical devices to support the failing circulation have been designed and are currently undergoing experimental and clinical trials.[22] In general, these are based on one of four physiologic principles: cardiac massage, counterpulsation, total or partial cardiac bypass, and cardiac replacement.

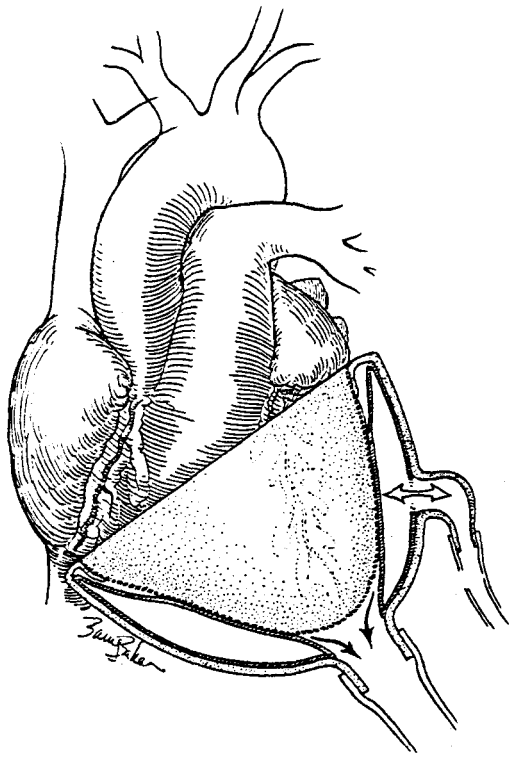

Fig. 9-1. Direct cardiac massage for the failing left ventricle by application of a cup with diaphragm around the heart.

CARDIAC MASSAGE

The ability to maintain satisfactory cardiac output with reasonable tissue perfusion by manual compression of the heart has long been appreciated. Cardiac massage may be accomplished internally by direct compression of the ventricles, but the external closed-chest method is more commonly used today. Prolonged use of either of these methods has obvious limitations.

As an outgrowth of the cardiac massage principle, application of a mechanical device around the ventricle for intermittent compression of the heart has been advocated.[1,2,21] A variety of such devices has been developed to provide temporary cardiac assistance by alternating positive and negative pressures between a cup and diaphragm encompassing the heart (Fig. 9-1). Theoretically, these devices provide systolic and diastolic cardiac assistance without creating the myocardial damage that results from direct cardiac massage. In clinical situations, cardiac output in excess of 4 liters per minute with support of normal systemic blood pressure has been maintained. The rapidity of application, apparent absence of tissue injury, and lack of need for anticoagulation make this a desirable method for temporary cardiac support. The major disadvantage, and probably limiting factor to its general use, is the need for thoracotomy for its insertion and removal. This is an especially important disadvantage in patients with acute myocardial infarction, but is not a consideration in patients requiring partial assistance after prosthetic valvular replacement or other cardiac procedures, because thoracotomy has already been performed.

COUNTERPULSATION (POSTSYSTOLIC MYOCARDIAL AUGMENTATION)

Several mechanical devices have been developed to reduce the resistance against which the left ventricle ejects blood during systole and to improve coronary arterial perfusion by raising diastolic pressure. This results in reduction of the tension-time index, cardiac work load, and oxygen consumption.

Arterial cannulation

The earliest clinical attempts at counterpulsation involved cannulation of the common femoral or iliac arteries for withdrawal and reinjection of blood.[24] Pneumatic driving mechanisms are triggered by the R wave of the electrocardiogram or by the ascending limb of the pressure pulse (Fig. 9-2). The need for exact synchronization may be a limiting factor to its use in patients with cardiac irregularities and hypotension. Moreover, most potential candidates for this method have advanced peripheral arteriosclerosis, which limits one's ability to withdraw rapidly and reinject a sufficient volume of blood. Since with this method the blood must leave the arterial system, the additional problems of anticoagulation and destruction of blood elements must be considered.

Intra-aortic balloon

Another form of diastolic augmentation that theoretically has none of these difficulties has recently been used to treat patients with cardiac failure due to acute myocardial infarction.[13,15] In this method an intra-aortic balloon is used to modify the pulse pressure in the aorta by synchronously changing the capacity

of the aorta for blood. A nonocclusive balloon is threaded through the common femoral artery to the level of the left subclavian artery. The pneumatic driving unit, which delivers a preset volume of carbon dioxide or helium to the balloon, is triggered by the R wave of the electrocardiogram (Fig. 9-3). The balloon is inflated during cardiac diastole so that blood is displaced and the aortic diastolic pressure is elevated. The increase in diastolic pressure produces a concomitant increase in coronary, carotid, and renal arterial blood flow[11] (Fig. 9-4). Deflation of the balloon during cardiac systole reduces the systolic blood pressure and increases the capacity of the aorta for blood. Experimental studies have shown that the extent of infarcted muscle after coronary ligation can be significantly reduced by early institution of balloon pumping.[23]

In the most extensive clinical experience with this form of cardiac assistance,[25] intra-aortic balloon support was not used in ten of twenty-six patients with myocardial infarction and cardiogenic shock because of (1) inability to introduce

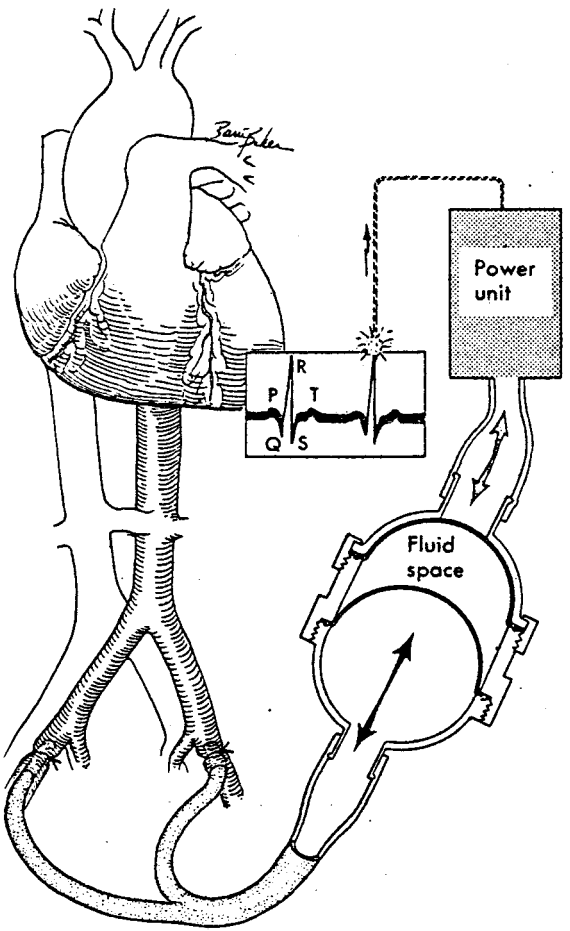

Fig. 9-2. Technique of counterpulsation, in which a quantity of blood is withdrawn rapidly during systole and is reinjected during diastole.

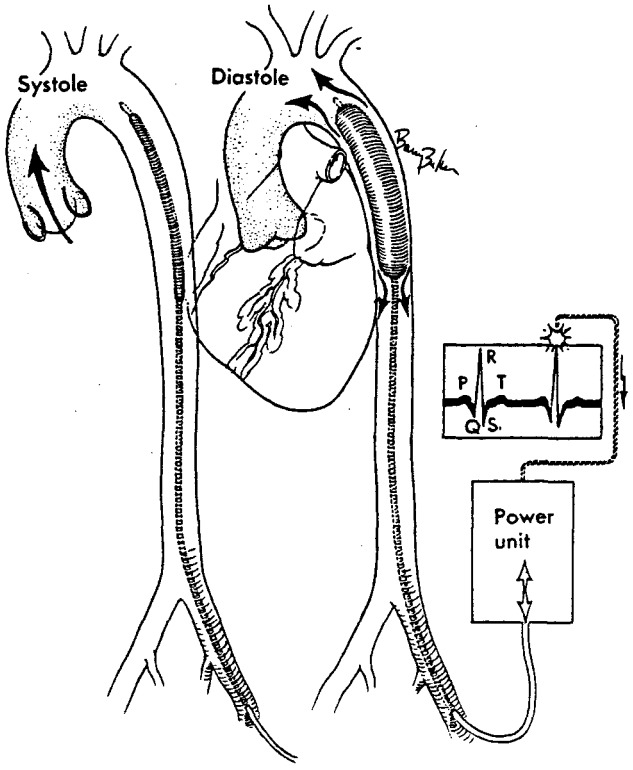

Fig. 9-3. Technique of diastolic augmentation with an intracardiac balloon placed at the level of the left subclavian artery. During diastole, the balloon expands and propels blood proximally and distally. During systole, the balloon collapses to permit unobstructed flow of blood.

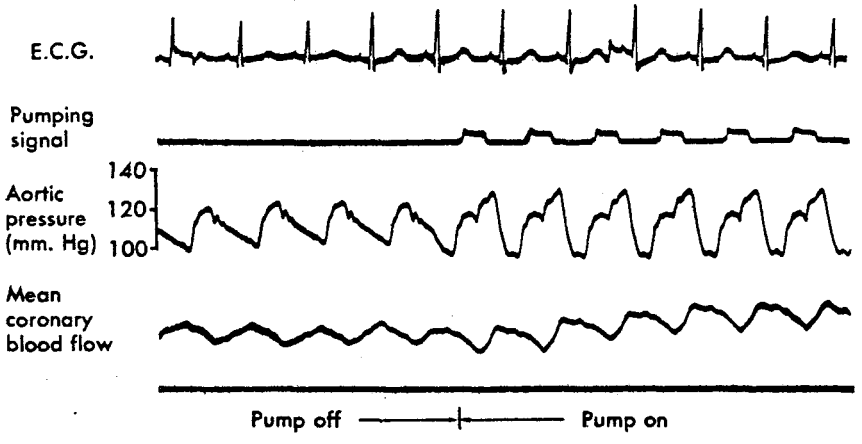

Fig. 9-4. Graph illustrating increased circumflex coronary arterial blood flow associated with diastolic augmentation using the intra-aortic balloon catheter. (From Diethrich, E. B., Liddicoat, J. E., Richardson, W. P., and DeBakey, M. E.: Cardiov. Res. Cent. Bull. 7:1969.)

the balloon, (2) death before pumping could be instituted, or (3) preference for continued medical treatment. All ten of these patients died. Cardiogenic shock was reversed in all but one of the sixteen patients treated by his method. Three patients died during interruption of the balloon pumping, and six died from 8 hours to 7 days after discontinuance of the pumping. The remaining seven patients were discharged from the hospital. Although this series is too limited to be of statistical significance, the results justify further clinical trial.

External counterpulsation

The disadvantages of arterial cannulation for intra-aortic balloon pumping and the need to withdraw blood and reinject it into a pumping unit in classic counterpulsation prompted studies of synchronous external assistance.[10,16,17,19] Since counterpulsation is actually a method of modifying aortic pressure during the cardiac cycle by displacement of blood, the same effects can be produced without an extracorporeal device if a portion of the vascular bed is substituted for the counterpulsating activator. In this method the lower body or legs are used to provide external pressure assistance to the left ventricle while the distribution of blood is controlled and the venous return and cardiac output are augmented. This form of external counterpulsation has been extensively investigated in the laboratory and awaits clinical trial.

CARDIOPULMONARY BYPASS

Most congenital and acquired cardiac lesions can now be surgically corrected with use of total cardiopulmonary bypass provided by the heart-lung machine (Fig. 9-5). Total cardiopulmonary bypass may be used for several hours with complete recovery of the patient. The duration of total cardiopulmonary bypass is definitely limited, however, since alterations in red blood cells and serum proteins are magnified as the duration of pumping and oxygenation of the blood is prolonged. It is hoped that current investigation directed toward development of pumps and oxygenating devices that inflict less trauma to the blood will extend the present temporal limitations of total cardiopulmonary bypass. Pulsatile pumps, which would resemble the heart's natural pumping characteristics more closely, and membrane oxygenators, which reduce the turbulence of the blood-gas interface, are fruitful areas for further study.

The sequence of events that occur during transition from total to partial cardiopulmonary bypass is observed during routine use of pump oxygenator equipment. As the tourniquet tapes around the superior and inferior venae cavae are released, and blood is permitted to flow into the right side of the heart, the left ventricle gradually assumes more and more of the cardiac output. For a period of time, the actions of the left ventricle and lungs are parallel to the pump oxygenator. The volume of blood delivered to the heart-lung machine is gradually reduced until finally the extracorporeal circuit is stopped. If the left ventricle is unable to resume a full work load, as evidenced by systemic hypotension and elevated right and left atrial pressures, partial cardiopulmonary bypass may be continued for temporary cardiac support.

The use of partial cardiopulmonary bypass for temporary support of cardiac

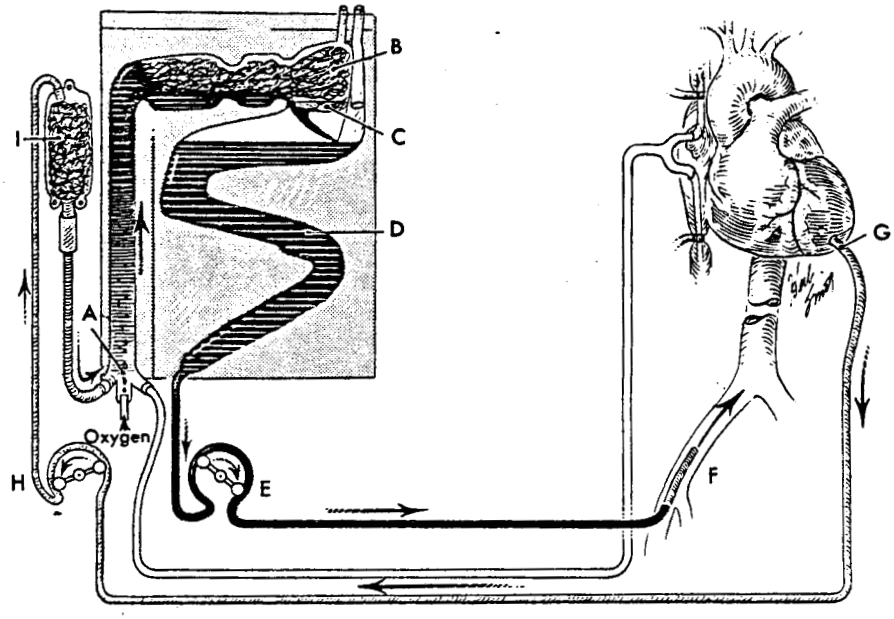

Fig. 9-5. Technique of total cardiopulmonary bypass used in correction of most congenital and acquired cardiac lesions. Oxygen is introduced into the oxygenator, where desaturated blood enters from the superior and inferior venae cavae *(A)*. Blood passes through the disposable bubble oxygenator, where it is defoamed and filtered, and air bubbles are evacuated *(B, C, D)*, before it is pumped *(E)* back to the arterial system through the femoral artery *(F)*.

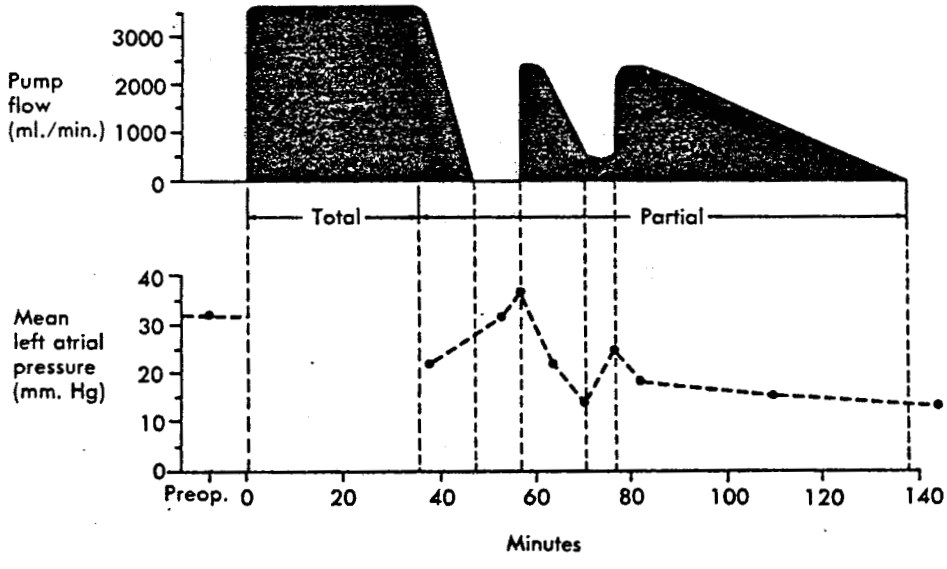

Fig. 9-6. Diagram and pressure recordings during use of partial cardiopulmonary bypass for temporary support after replacement of the mitral valve. (From DeBakey, M. E., and Diethrich, E. B.: Cardiac assistors. In Cooper, P., editor: Surgery annual, New York, Appleton-Century-Crofts. To be published.)

function is illustrated in Fig. 9-6. A 50-year-old man with severe mitral valvular stenosis and insufficiency underwent resection of the mitral valve and prosthetic valvular replacement. The duration of total cardiopulmonary bypass required for mitral valvular replacement was 47 minutes. On completion of the operation and discontinuance of cardiopulmonary bypass, the left atrial pressure rose to 36 mm. Hg, as contrasted with the preoperative pressure of 32 mm. Hg. The right atrial pressure rose and the systemic arterial pressure fell. Partial cardiopulmonary bypass was immediately reestablished at a flow rate of 2,500 ml./minute. As the left atrial pressure fell to 14 mm. Hg, the flow rate of the pump was reduced to 500 ml./minute; however, a gradual rise of left atrial pressure

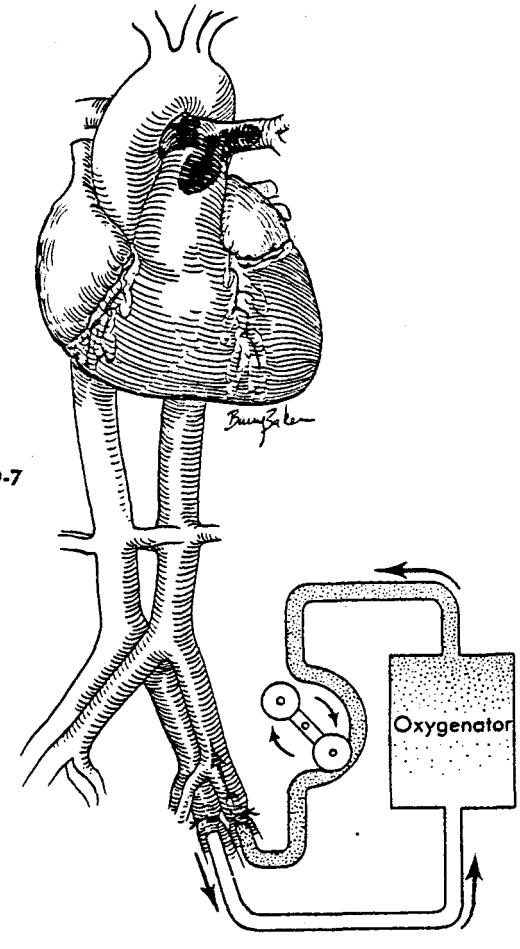

Fig. 9-7

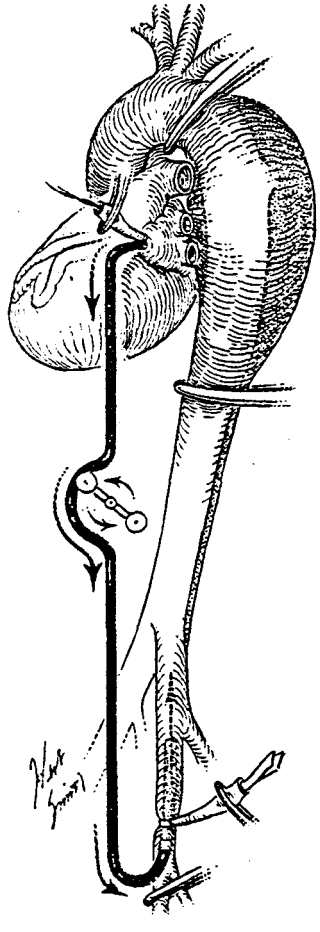

Fig. 9-8

Fig. 9-7. Partial cardiopulmonary bypass with peripheral cannulation of femoral artery and vein used in treatment of acute pulmonary embolism. This procedure is effective in overcoming right ventricular strain associated with outflow obstruction and can be converted to total cardiopulmonary bypass during embolectomy.

Fig. 9-8. Technique of partial left cardiac bypass (left atrium to femoral artery) used during resection and graft replacement of aneurysm of descending thoracic aorta.

to 25 mm. Hg indicated inability of the left ventricle to support the entire cardiac output. The flow rate of the pump was increased to 2,500 ml./minute for 30 minutes and then gradually reduced as the left atrial pressure fell and remained stable at 15 mm. Hg. Partial cardiopulmonary support was continued for 1 hour, after which cardiac function was satisfactory, and the pump was turned off.

This case illustrates the value of partial cardiopulmonary bypass in assisting the left ventricle during the immediate period after valvular replacement. Without such support, the left ventricle cannot maintain adequate cardiac function, and a vicious cycle of hypotension, acidosis, and further cardiac injury occurs. Eventually, the myocardial damage and left ventricular failure become irreversible. Detection of ventricular failure in such patients, by persistent elevation of left atrial pressure and systemic hypotension, is imperative so that corrective measures may be instituted at the appropriate time.

Partial cardiopulmonary bypass has effectively relieved acute right ventricular

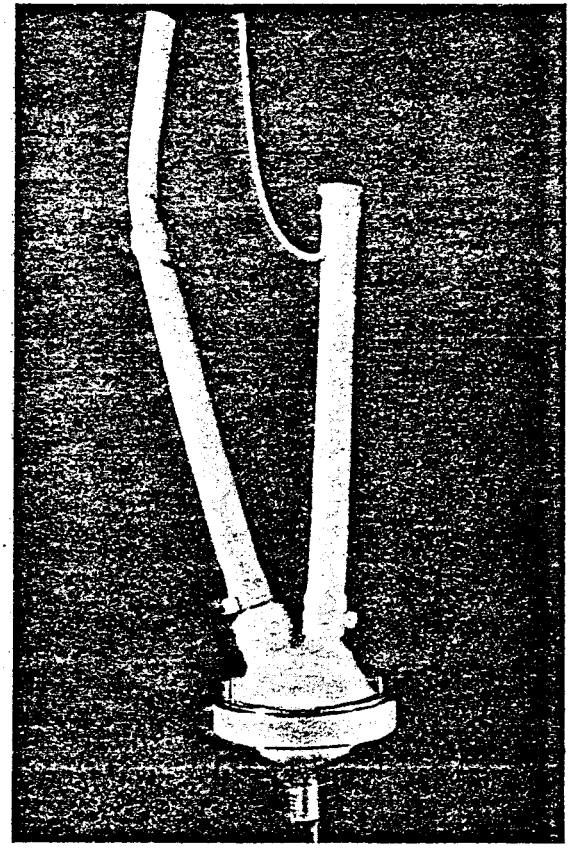

Fig. 9-9. Left ventricular bypass pump used for assistance after cardiac valvular replacement. (From DeBakey, M. E., and Diethrich, E. B.: Cardiac assistors: In Cooper, P. editor: Surgery annual, New York, Appleton-Century-Crofts. To be published.)

failure due to pulmonary embolism. It has usually been accomplished by peripheral cannulation of the femoral artery and vein for veno-arterial perfusion with oxygenation (Fig. 9-7). Unfortunately, the procedure has been less effective in acute left ventricular failure due to myocardial infarction. Under these circumstances, there has been no evidence of improved cardiac function, since the failing left ventricle must maintain the cardiac output and open the aortic valve against the elevated pressure developed by the pump perfusing retrograde through the femoral artery. The maximum benefit appears to be improvement of peripheral circulation with increase in hepatic and renal blood flow rather than increase in myocardial perfusion and reduction of left ventricular work load. Veno-arterial pumping with oxygenation has been used clinically with some success when the reinjection of blood is synchronized electrocardiograph-

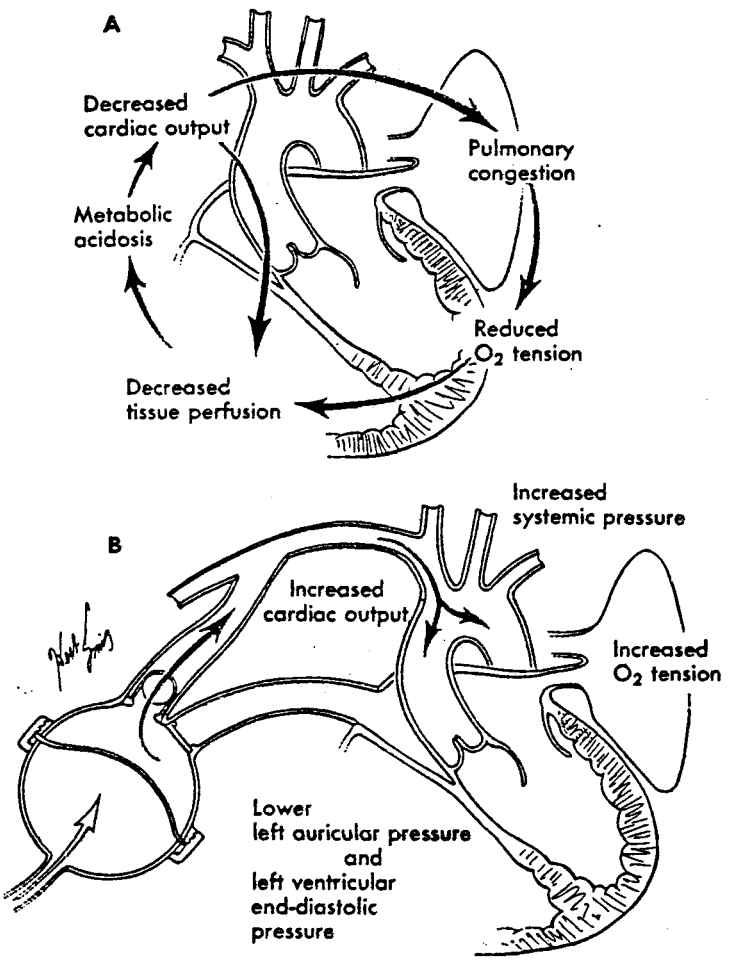

Fig. 9-10. A, Metabolic changes consequent to the hemodynamic disturbances resultant from left ventricular failure. B, Left ventricular bypass pump breaks this vicious cycle by lowering left atrial pressure with consequent reduction in left ventricular end-diastolic pressure.

ically with diastole. Destruction of blood as a result of prolonged extracorporeal pumping and oxygenation is still an inherent problem of this method.

Left atriofemoral bypass is used routinely to perfuse abdominal viscera and the spinal cord and to relieve proximal hypertension during resection of aneurysms of the descending thoracic aorta and graft replacement (Fig. 9-8). Application of this procedure for prolonged circulatory assistance is logical, since a volume of blood is removed from the left atrium and returned to the femoral artery with resultant reduction in the left ventricular volume, pressure, and work load. The left ventricular bypass pump (Fig. 9-9) operates in a manner similar to that of the roller pump used for atriofemoral bypass, its basic function being to relieve left ventricular strain and permit recuperation after correction of the fundamental cause of the cardiac failure.

Inability of the left ventricle to empty effectively during systole results in decreased cardiac output, increased end-diastolic pressure, and lowered systemic pressure. Filling of the left atrium is inhibited, the result being elevation of pulmonary venous pressure leading to pulmonary congestion. If these conditions are not corrected, a series of complex metabolic events occurs (Fig. 9-10, *A*). Pulmonary congestion causes reduced arterial oxygen tension, which further decreases adequacy of tissue perfusion already impaired by reduced cardiac output. The resulting profound metabolic acidosis further impairs cardiac function and causes hypoxemia, acidosis, cardiac arrhythmia, and death.

This cycle may be immediately broken by use of the left ventricular bypass

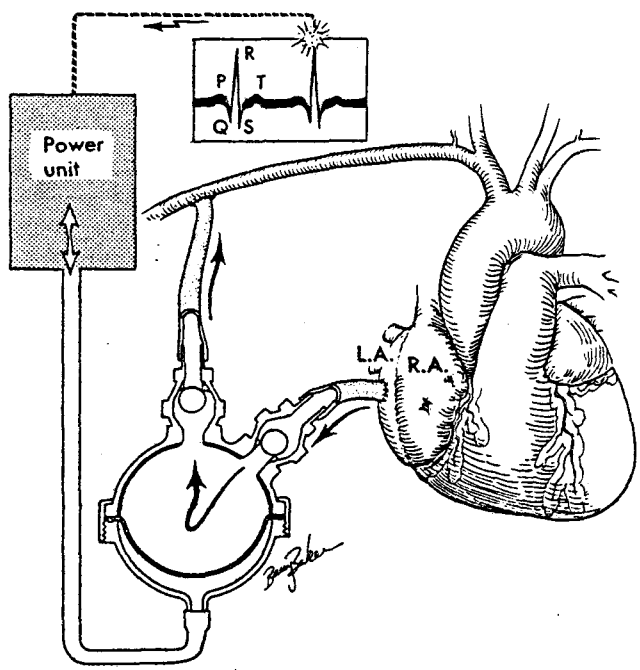

Fig. 9-11. Use of left ventricular bypass pump for circulatory assistance after replacement of aortic valve. Power unit is synchronized with the electrocardiogram.

pump, resulting in lowering of left atrial pressure and consequent reduction of left ventricular end-diastolic pressure (Fig. 9-10, *B*). Pulmonary congestion is relieved, and the arterial oxygen tension is improved, with subsequent increase in cardiac output, coronary blood flow, and myocardial perfusion.

The left ventricular bypass principle has been applied clinically by use of left atrial cannulation across the atrial septum from the jugular vein or by direct anastomosis of a cannula to the left atrial wall. In both methods, the atrial cannulas are attached to a pump, and blood is returned to the body through a peripheral artery. A gas-energized left ventricular bypass pump (Fig. 9-11) has been developed for use with the latter method. This hemispherically designed pump has a molded diaphragm separating the gas and blood chambers. The lining of the interior surfaces of both the pumping chamber and the connecting tubes is made of Dacron velour to provide a more satisfactory blood interface and thereby reduce the need for systemic anticoagulation during use of the pump. This pump may be controlled manually or by an electrocardiographic triggering mechanism.

The technique of application of the left ventricular bypass pump to the patient is illustrated in Fig. 9-12. A Dacron velour tube is attached to the left

Fig. 9-12. Steps in connecting left ventricular bypass pump after valvular replacement. Dacron velour tube is sutured to left atrium after closure of the left atrial suture line and is passed through an intercostal space. A second Dacron velour tube (*A*) is anastomosed to the axillary artery (*B*), and connections are made with the pump. The gas line is secured, the pump is primed, and the diaphragm is slowly activated by manual control (*C*).

atrium, clamped at the atrial suture line, passed between the fifth and sixth ribs, and connected to the inflow site of the pump. A second Dacron velour tube is anastomosed to the axillary artery and connected to the outflow site of the pump, which is primed with 5% dextrose solution. The gas line is secured to the pump, and the diaphragm is slowly activated manually until the desired pumping rate is reached, when electrocardiographic synchronization is established.

Use of the left ventricular bypass pump after mitral valvular replacement in a 16-year-old girl with mitral stenosis and insufficiency is illustrated in Fig. 9-13. Valvular replacement required total cardiopulmonary bypass at a flow rate of 3,500 ml./minute for 40 minutes. After replacement, left atrial pressure fell to 25 mm. Hg, and partial bypass was gradually decreased until it was discontinued. Within 5 minutes, the left atrial pressure rose to 35 mm. Hg and the mean arterial pressure fell from 80 to 50 mm. Hg. Resumption of partial cardiopulmonary bypass at a flow rate of 2,500 ml./minute resulted in a drop in left atrial pressure to 30 mm. Hg and a rise in mean arterial pressure to 70 mm. Hg. Partial bypass was then gradually reduced to 800 ml./minute; however, left atrial pressure began to rise again, and the arterial pressure continued to fall. It was therefore decided that the patient required more prolonged circulatory assistance, and the left ventricular bypass pump was applied.

Partial cardiopulmonary bypass was gradually reduced during the next 30 minutes as the flow rate of the left ventricular bypass pump was increased to 1,200 ml./minute. At this point, mean arterial pressure was 90 mm. Hg, central venous pressure 20 mm. Hg, and left atrial pressure 28 mm. Hg. Cardiopulmonary bypass was discontinued, vena caval and femoral cannulas were removed, and protamine was administered to restore normal coagulation of the blood.

Fifteen hours after operation, the rate of the pump was slowed to 800 ml./minute, but gradual rise of left atrial pressure to 26 mm. Hg necessitated

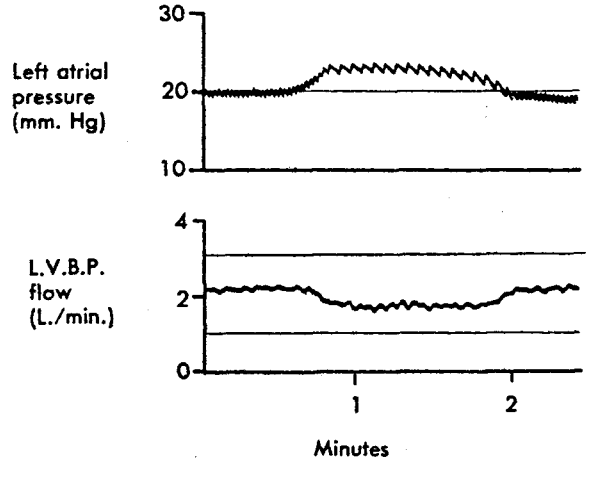

Fig. 9-13. Graph of left atrial pressure curves, illustrating effect of left ventricular bypass pump after replacement of mitral valve.

increasing the rate to 1,200 ml./minute. Twenty-seven hours after operation, with the left atrial pressure at 15 mm. Hg, the flow rate was again slowly reduced to 800 ml./minute without a subsequent rise in left atrial pressure. The flow rate was reduced gradually. By the morning of the third day after operation it reached 600 ml./minute with a left atrial pressure of 7 mm. Hg, and on the fourth day after operation use of the pump was discontinued without increase in left atrial pressure. The pump was then removed, and the patient made a complete recovery.

This and other similar cases have demonstrated the value of temporary cardiac assistance with the left ventricular bypass pump. On several occasions, depressed renal function due to low cardiac output has been reversed by increasing the flow rate of the bypass pump. Similarly, acute pulmonary edema after valvular replacement has been corrected by reducing left atrial pressure within the bypass pump. The necessity of thoracotomy to apply the pump has limited its use to cardiac support after valvular replacement. Further experience

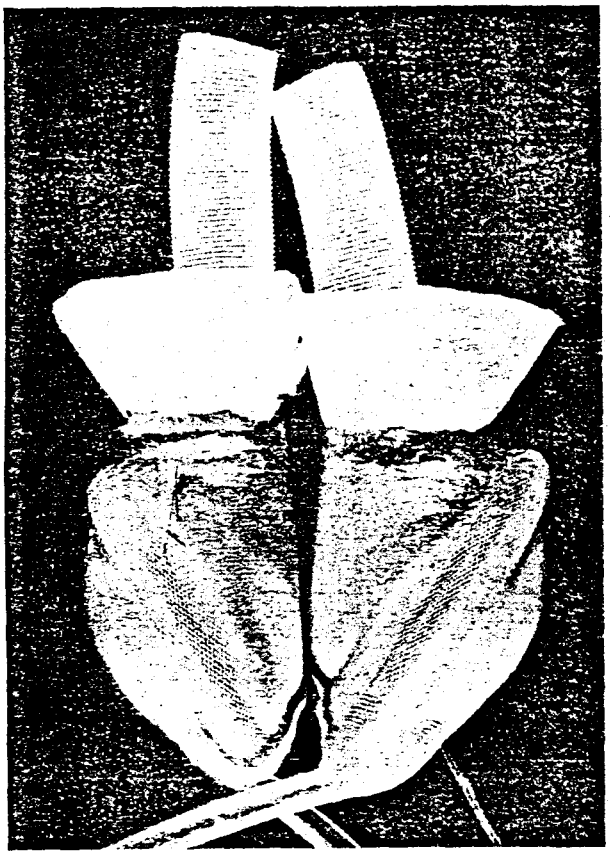

Fig. 9-14. Ventricular surfaces of pumping chamber used for total cardiac replacement. (From DeBakey, M. E., Hall, C. W., Hellums, J. D., O'Bannon, W., Bourland, H., Feldman, L., Wieting, D., Calvin, S., Smith, P., and Anderson, S.: Cardiov. Res. Cent. Bull. 7, April-June, 1969.)

and modifications in design should provide opportunities to extend clinical application of the left ventricular bypass principle.

CARDIAC REPLACEMENT

Total cardiac replacement with a prosthetic pumping device represents the final goal in the development of cardiac assistors. Extensive research and clinical experience with the various forms of cardiac assistors, especially the left ventricular bypass pump, have demonstrated the feasibility of total mechanical cardiac replacement. Problems in control, fabrication, materials, and power source currently under investigation will require solution before clinical application is possible. Orthotopic cardiac replacement with a device that has two parallel pumping chambers (Figs. 9-14 and 9-15) is currently being investigated in the calf.

The operative technique of implantation consists in removal of the entire recipient's heart, but the posterior right and left atrial walls, interatrial septum, ascending aorta, and main pulmonary artery are left intact. Anastomosis of the prosthetic heart to these structures is similar to that used in homograft cardiac transplantation (Fig. 9-16). The blood circuit through the pump is shown in Fig. 9-17. Like the left ventricular bypass pump, each pumping chamber is connected to an external power source, and the right and left pumping chambers are controlled by individual pressure regulators (Fig. 9-18). Fig. 9-19 shows the physiologic recordings in a typical experiment in which the aortic pressure, mean left atrial pressure, and aortic flow were monitored. The prosthetic heart can maintain normal aortic pressure with cardiac output in excess of 10 liters

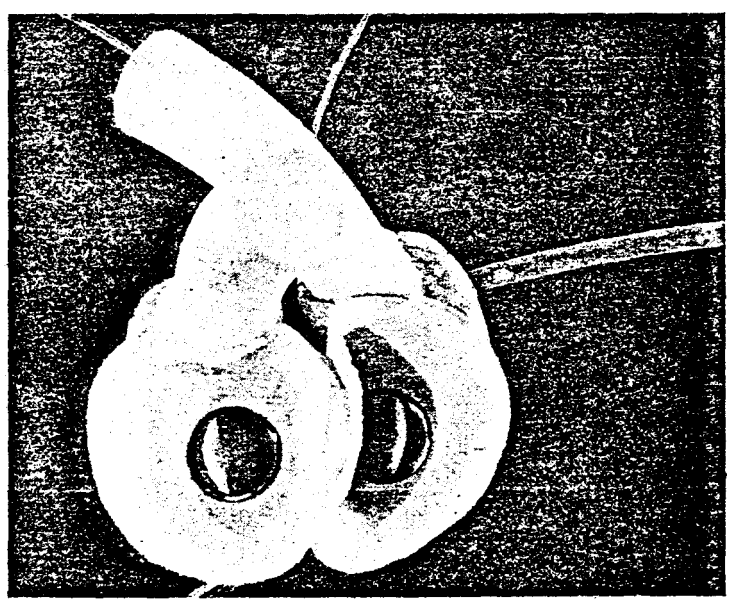

Fig. 9-15. *Atrial surfaces with valves used for total cardiac replacement.* (From DeBakey, M. E., et al.: Cardiov. Res. Cent. Bull. 7, April-June, 1969.)

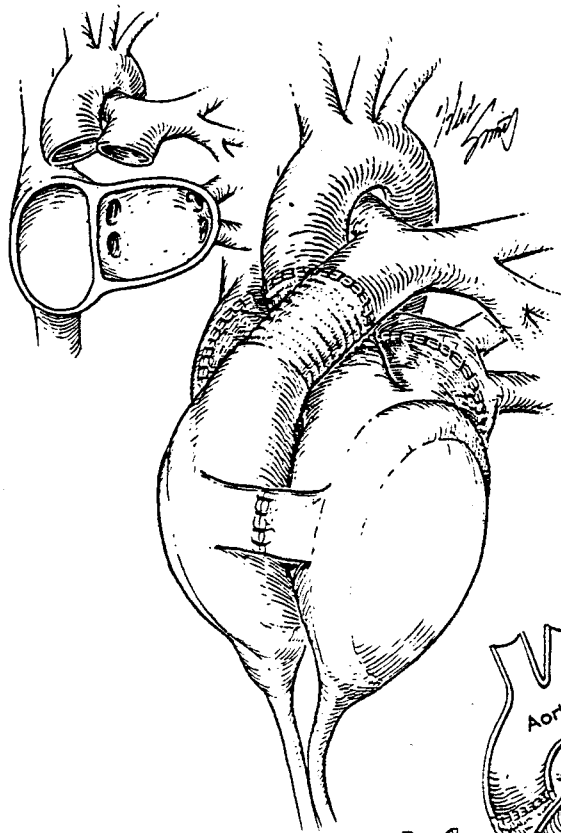

Fig. 9-16

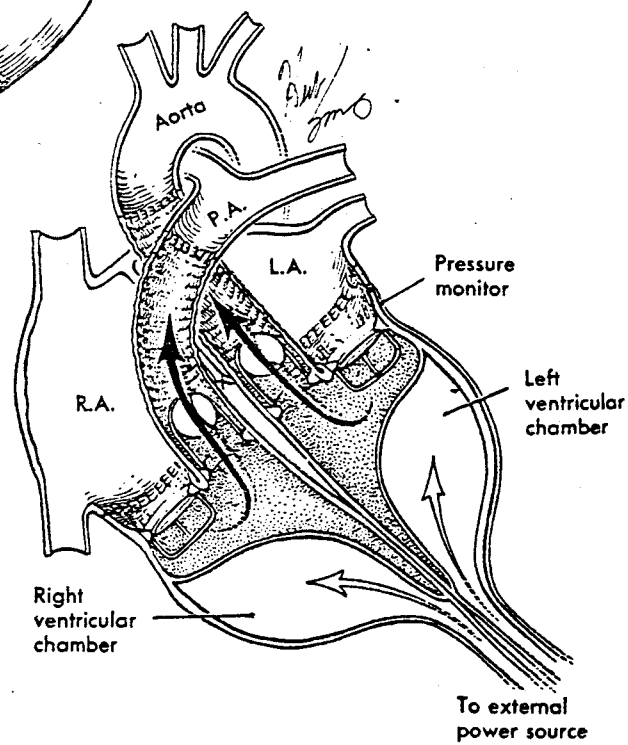

Fig. 9-17

Fig. 9-16. Technique of anastomosing right and left pumping chambers to posterior atrial walls, interatrial septum, pulmonary artery, and aorta. (From DeBakey, M. E., et al.: Cardiov. Res. Cent. Bull. 7, April-June, 1969.)

Fig. 9-17. Blood circuit through the right and left pumping chambers. (From DeBakey, M. E., et al.: Cardiov. Res. Cent. Bull. 7, April-June, 1969.)

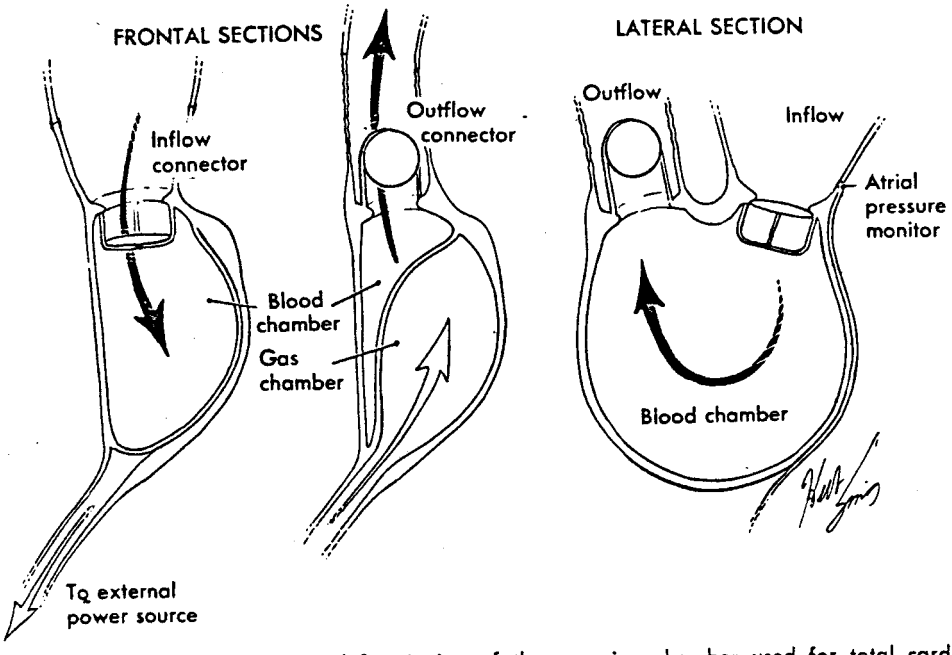

Fig. 9-18. Chambers, valving, and functioning of the pumping chamber used for total cardiac replacement. (From DeBakey, M. E., et al.: Cardiov. Res. Cent. Bull. 7, April-June, 1969.)

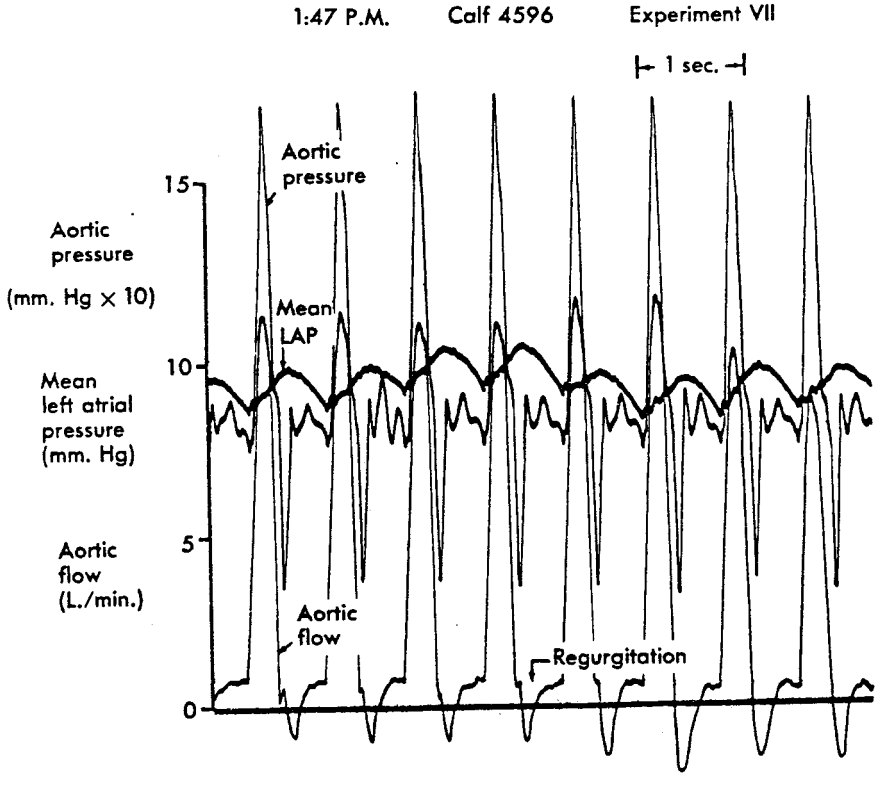

Fig. 9-19. Graph illustrating aortic and left atrial pressures and cardiac output obtained using two pumping chambers for total cardiac replacement in calf. (From DeBakey, M. E., et al.: Cardiov. Res. Cent. Bull. 7, April-June, 1969.)

per minute. Survival of calves with this mechanical heart has been limited to 12½ hours. As further experience is gained in both the fabricating and the control of this and similar devices, the duration of survival should be longer.

CONCLUSION

Although these four methods of cardiac assistance—cardiac massage, counterpulsation, total or partial cardiac bypass, and cardiac replacement—are dissimilar in many respects, the fundamental goal of each is reversal of left ventricular failure and reestablishment of normal cardiovascular hemodynamics. Each method has salient advantages and disadvantages, and only by the continuing combined efforts of medical and engineering scientists will the problems of assisted circulation be solved. Possibly, not one but several methods may evolve, the application of each depending upon the individual clinical situation. Early clinical success with some cardiac assistors, although limited, clearly indicates that assisting the failing heart for long periods of time with total cardiac replacement is a distinct possibility.

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